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# Controlling the State of a Reverberation Chamber by means of a Random Multiple-Antenna Stirring

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**Abstract**—In this paper we introduce a novel technique based on the random excitation of several antennas. As opposed to previous attempts at this approach, the random signals are correlated by means of a pre-conditioning filter, in order to increase the number of accessible degrees of freedom and optimize the covariance matrix of the field measured in the chamber. A dramatic improvement is observed at those frequencies where standard mechanical stirrers fail.

**Index Terms**—Cavities, stochastic fields, test facilities.

## I. INTRODUCTION

One of the biggest obstacles to the extension of use of mode-stirred reverberation chambers (MSRC) is certainly the lack of effective stirring techniques in the lower frequency range of these facilities [1], [2], [3]. The reasons are due to the inability of mechanical and frequency stirring techniques to effectively affect the field distribution of a cavity when the latter does not support a diffused field anymore [4].

In order to understand the origin of these limitations, we shall recall the modal theory of a cavity. The electric field generated within a cavity occupying a region of space  $\Omega$  can be linked to the excitation sources by means of the dyadic Green function of the medium  $\underline{\mathbf{G}}_{ee}(\mathbf{r}, \mathbf{r}')$ , which is conveniently represented under a spectral expansion [5]

$$\underline{\mathbf{G}}_{ee}(\mathbf{r}, \mathbf{r}') = \sum_{n=1}^{\infty} \frac{\mathbf{e}_n(\mathbf{r})\mathbf{e}_n(\mathbf{r}')}{k^2 - k_n^2}, \quad (1)$$

where  $\{\mathbf{e}_n(\mathbf{r})\}$  are the normal modes of the cavity, i.e., the eigensolutions of Helmholtz equation, whereas  $\{k_n\}$  are its eigenvalues, representing the frequencies of resonance of the cavity. In a general manner  $k_n \in \mathbb{C}$ ; in the context of reverberating cavities, the imaginary part of  $\{k_n\}$  can be assumed to be much smaller than their real part, because of weakly lossy materials.

The electric field generated by electric sources  $\mathbf{J}(\mathbf{r})$  is thus given by

$$\mathbf{E}(\mathbf{r}) = \int_{\Omega} \underline{\mathbf{G}}_{ee}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}(\mathbf{r}') d^3\mathbf{r}', \quad (2)$$

where only sources represented by electric current distributions have been considered, without any loss of generality. It is

convenient to write (2) as

$$\mathbf{E}(\mathbf{r}) = \sum_{n=1}^{\infty} \frac{\gamma_n \mathbf{e}_n(\mathbf{r})}{k^2 - k_n^2} \quad (3)$$

with

$$\gamma_n = \int_{\Omega} \mathbf{e}_n(\mathbf{r}') \cdot \mathbf{J}(\mathbf{r}') d^3\mathbf{r}' \quad (4)$$

the modal weights.

Most stirring techniques operate by modifying the boundaries of  $\Omega$ , which leads to a modification of the normal modes  $\{\mathbf{e}_n(\mathbf{r})\}$  and, ultimately, of the modal weights  $\{\gamma_n\}$ , through (4). This twofold modification of the modal quantities is intended to provide a randomization of the field distribution within the MSRC. Such approach is effective only as long as these modifications are based on displacements (sources, scatterers, walls, stirrers, etc.) of the order of at least half a wavelength. In a similar manner, frequency stirring exploits the modification of resonant propagation paths as the working frequency is modified: again, this type of technique is effective only if these modifications account for a significant additional phase-shift, i.e., an incremental path length of a non-negligible fraction of wavelength.

The failure of these techniques in the lower frequency range are therefore inevitable, since for a fixed absolute modification (e.g., a displacement), the corresponding electric modification (phase shift) will reduce as the frequency decreases. Still, these problems do not mean that the field cannot be modified. Looking more closely at (3), it appears that a direct modification of the modal weights could allow a non-negligible modification of the electric field distribution. But as we just recalled, stirring techniques usually do not operate by a direct modification of the  $\{\gamma_n\}$ , but rather indirectly by affecting the normal modes  $\{\mathbf{e}_n(\mathbf{r})\}$ . As soon as this strategy fails, modal weights are no longer accessible.

The aim of this work is to introduce a novel stirring technique allowing a direct modification of the modal weights, thus providing a much stronger field randomization even though no mechanical displacement is considered. It will be shown that by the same token the field statistics can be optimized in order to dramatically improve the field uniformity at lower frequencies. We call this technique Multiple-Antenna Stirring (MAS).

## II. MULTIPLE-ANTENNA STIRRING

Let us consider a cavity operated in its lower frequency region, where it is no longer possible to assume wave-diffusive features, as those expected for a scattering-rich random medium [4], even though the cavity is still electrical large. This condition requires the availability and accessibility of a large (ideally infinite) number of degrees of freedom. These are nothing more than the normal modes of the cavity.

The typical modal structure encountered in this case is actually worse. In practice, even in the case where a non-negligible number of modes is available, it appears that just a few dominate the field distribution, with modal weights that are hardly modified, e.g., by changing the position of the sources or operating a mechanical stirrer. An example of this trend is provided in the next Section.

What happens if we ponder the eventual advantages of using multiple sources? This idea was already tried out in a previous paper[6], by applying independent narrow-band excitations to the antennas. Due to the existence of these dominant modes, the distributed excitation of the cavity cannot provide any improvement with respect to a single-case configuration, because all of these sources are mainly operating over the same few modes. As a result, field uniformity is hardly affected, and the only advantage is the fact that the total injected power  $P_{\text{in}}$  is now distributed over  $N_a$  antennas.

The problem can thus be stated as follows: is there any way to design excitation signals for a multiple-antenna setup, capable of exciting all of the available degrees of freedom with the same effectiveness? The answer to this question is thus straightforward: we should chose the excitation signals from the subspace defined by the normal modes that are actually controllable. To this effect, we need the ability to observe them, hence the need for *a priori* information, typically in the shape of measurements. To this effect, it is a good idea to recall that in the framework of the IEC standard [7] field uniformity is one of the most important figures of merit. Without discussing the fine details of its definition, we can nevertheless say that it is based on measurements taken over the 8 corners of a rectangular cuboid defining the test volume. Three field components (usually Cartesian) are measured at each corner, making a grand total of 24 field samples. These are then multiplied by the number of realization generated by a stirring technique.

For the purpose of our study, based on the idea of stirring only the modal weights, and not the modal distributions  $\{e_n(\mathbf{r})\}$ , we just need to consider a single configuration. We can thus juxtapose the 24 scalar field samples into a vector  $\mathbf{E}_{24} \in \mathbb{C}^{24 \times 1}$ , and link them to the incident power waves (excitation)  $\{a_n\}$  applied to the  $N_a$  antenna input ports

$$\mathbf{E}_{24} = \mathbf{H}\mathbf{a}, \quad (5)$$

where  $\mathbf{a}$  is the vector containing the antenna excitations and  $\mathbf{H} \in \mathbb{C}^{24 \times N_a}$  is a generalized transfer function, obtained from the original field measurements during the calibration phase of the static MSRC. The singular values of  $\mathbf{H}$  are a direct measure of how strongly each mode is coupled to the excitation antennas.

The random excitation of the modes is not useful per se, unless done in such a way as to generate a field distribution appearing as a Gaussian random process, with statistical moments independent from the spatial position, at least over the test volume. This need can be formalized by considering the covariance matrix  $\mathbf{C}_E$  of the random vector  $\mathbf{E}_{24}$ , defined as

$$\mathbf{C}_E = \mathbf{E} \left[ \mathbf{E}_{24} \mathbf{E}_{24}^H \right], \quad (6)$$

where  $\mathbf{E}[\cdot]$  is the ensemble average operator. In order to ensure spatial uniformity of the field statistical moments, depolarization (or isotropy) and independence of the field samples, we shall require

$$\mathbf{C}_E = E_0^2 \mathbf{1} \quad (7)$$

with  $\mathbf{1}$  the identity matrix and  $E_0^2$  the variance of the field. Inserting (5) into (6),

$$\mathbf{C}_E = \mathbf{H} \mathbf{C}_a \mathbf{H}^H, \quad (8)$$

with  $\mathbf{C}_a$  the covariance matrix of the excitation signals. Therefore (7) requires solving

$$E_0^2 \mathbf{1} = \mathbf{H} \mathbf{C}_a \mathbf{H}^H, \quad (9)$$

with respect to  $\mathbf{C}_a$ , i.e., designing excitation signals correlated in such a way as to ensure a covariance matrix for the field samples proportional to the identity matrix. It is clear from (8) that the choice of using independent random excitations could not provide a solution, since the covariance matrix would be given by  $\mathbf{H} \mathbf{H}^H$ , which is unlikely to approximate an identity matrix, unless an infinite number of modes were available, since this is in contradiction with our starting point. We will rather apply a least-square approach, by multiplying at the left of (9) by  $\mathbf{H}^H$  and at its right by  $\mathbf{H}$ , which allows us to write

$$\mathbf{C}_a = E_0^2 \left( \mathbf{H}^H \mathbf{H} \right)^{-1}, \quad (10)$$

where the equal sign is to be intended as a least-square solution. This solution is consistent as long as the transfer functions between the excitation antennas and the positions at which the field samples were measured are linearly independent, i.e., non redundant. This requires the necessary (but not sufficient) condition that the position between any two antennas be at least one wavelength away, in order to reduce the spatial correlation.

Random excitation signals obeying (10) can be defined by first generating independent and identically distributed signals  $\mathbf{x} \in \mathbb{C}^{N_a \times 1}$ , and then filtering them through a passage matrix  $\mathbf{P} \in \mathbb{C}^{N_a \times N_a}$ , defined as

$$\mathbf{P} = \sqrt{\left( \mathbf{H}^H \mathbf{H} \right)^{-1}}, \quad (11)$$

yielding

$$\mathbf{a} = \mathbf{P} \mathbf{x}. \quad (12)$$

Hence, the best approximation of (7) will be

$$\mathbf{C}_E = \mathbf{H} \left( \mathbf{H}^H \mathbf{H} \right)^{-1} \mathbf{H}^H, \quad (13)$$

which is now a true equality. Since the rank of the excitation covariance matrix is bounded by  $N_a$ , the rank of  $\mathbf{C}_E$  will

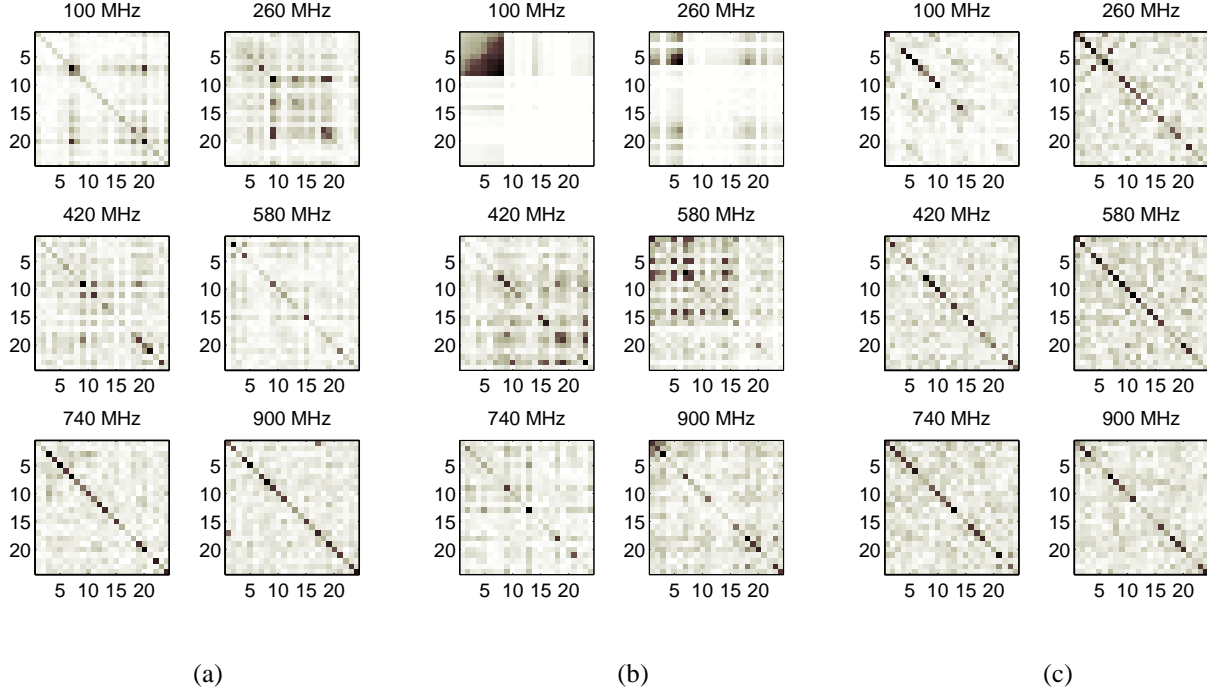


Fig. 1: Covariance matrices for the 24 scalar field samples measured at the corners of the test volume, as observed for three stirring techniques: (a) mechanical stirrer; (b) MAS with random BPSK modulation; (c) MAS with a correlated modulation. The MAS results involved the use of 8 antennas.

follow suite. It is therefore impossible to perfectly solve (7) and a residual correlation and disparities will appear in practice. The mathematical meaning of (12) is to generate random excitations aligned to the singular vectors of  $\mathbf{H}$ , allowing one to excite with equal effectiveness all of the available degrees of freedom of the cavity.

A last important point : this solution should not be regarded as only capable of enforcing the right field statistics over the corners of the test volume, but rather as a mean of generating random modal weights, thus implying a more global effect of the proposed technique. As a matter of fact, with the modal distributions  $\{e_n(\mathbf{r})\}$  not modified by any mechanical process, the only way of obtaining a random field distribution is to directly operate over the modal weights. Hence, the benefits of the proposed technique will be observable on neighboring positions, too.

### III. EXPERIMENTAL VALIDATION

These ideas were tested by measuring the transfer function  $\mathbf{H}$  within Supelec's 13.3 m<sup>3</sup> reverberation chamber. The test volume was previously identified by applying the standard procedure required in [7]. A total of eight monocone antennas were mounted at random positions along the walls of the MSRC, while a styrofoam support was used in order to ensure a stable positioning of a EFS-105 (Enprobe) field probe. The linear polarization of the probe allowed a precise measurement of the 24 transfer functions needed to apply our method. Since 8 antennas are involved, the collection of the  $24 \times 8$  transfer

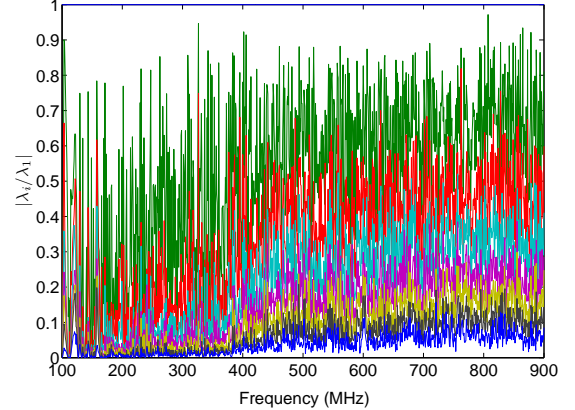


Fig. 2: Normalized intensity of the eigenvalues of  $\mathbf{H}^H \mathbf{H}$  versus frequency.

functions was ensured by the use of electronic switches, scanning the antennas.

So far, we have not yet implemented the full electronic system required for the generation of the excitation signals. Since the system under consideration is linear, this is not an obstacle to the validation of the technique, once the transfer functions are known. Hence, we have considered harmonic signals described by random phasors  $\alpha$  as derived in the previous Section: this corresponds to applying a modulation scheme to an input harmonic signal serving as a reference shared by all of the antenna inputs. Two strategies were considered: 1)

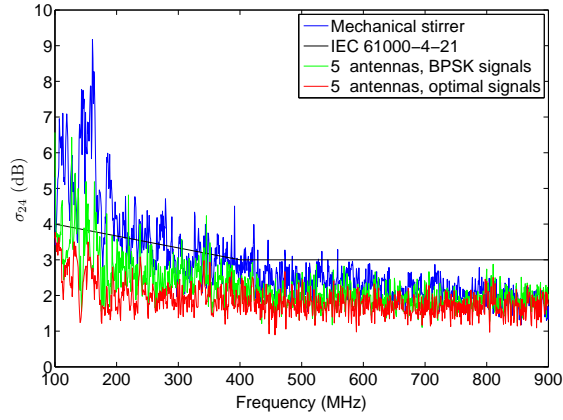


Fig. 3: Comparison of the field uniformity generated by means of three stirring techniques, as discussed in Fig. 1, but with 5 antennas. The maximum deviation allowed by the IEC standard [7] is shown as a thick black line.

the signals were modulated by randomly switching over two possible states, with a fixed amplitude and just a change in the sign of the phase (i.e., a BPSK modulation), without using any previous knowledge obtained from the transfer function  $\mathbf{H}$ ; 2) these signals were subsequently filtered (or weighted) by the matrix  $\mathbf{P}$ , thus making them correlated.

Knowing  $\mathbf{H}$ , the computation of the resulting field samples in the two cases is trivial. After generating 100 random realizations, we applied the standard procedure for assessing the field uniformity, i.e., by keeping the maximum generated by the two methods, and eventually computing their spatial uniformity  $\sigma_{24}$ . The results of this operation are shown in Fig. 3, where the results obtained by using a standard setup with a mechanical stirrer serve as a reference (with the field samples measured over the same positions as for the alternative technique). These results clearly prove that the proposed technique is viable and that it is very effective in improving the field uniformity within a MSRC, even at frequencies well below the original LUF obtained with the mechanical stirrer. Of particular interest is the fact that the use of the matrix  $\mathbf{P}$  to correlate the excitation signals smooths out the local non-compliances observed with a direct random excitation of the antennas.

The degrees of freedom available were also computed, and are shown in Fig. 2: indeed, as the frequency decreases, there is often just a couple of dominant degrees of freedom. The frequencies at which this number decreases is well correlated with those frequencies where the standard deviation of the BPSK excitations present spikes. This is far from surprising.

A last important result is provided by the covariance matrix of the field samples, shown in Fig. 1. Here the shortcomings of the mechanical stirring are clearly represented by the existence of strong spatial correlations between samples at different positions/orientations, particularly at low frequency. The use of independent random excitation signals is shown to have a poor performance, even at relatively high frequencies. The existence of dominant modes is apparent at low frequency.

By contrast, the optimal correlated signals ensure a very weak spatial correlation even at the lowest frequency.

Of course this technique is not exempted from limitations. The first point to highlight is the fact that for correlated signals, the power contributed by each antenna cannot be summed up: as a results, the energy efficiency of this technique should be expected to be lower than that of independent excitations. Indeed, part of the power of the input signals is used in order to generate complex excitation patterns intended to reduce the fraction of power coupling to the dominant modes. The second issue is the need for a calibration phase. Although this might appear as a step increasing the overall duration of the test, two points should be pondered: 1) the subsequent tests will require no mechanical displacement, thus faster; 2) this calibration phase is by no means comparable in complexity and time duration to the calibration of a standard MSRC. Indeed, these measurements are carried out within a static configuration, so that it takes just a few minutes!

A final point: the alternative is very poor field uniformity at frequency below LUF, hence the advantages of the proposed technique outweigh its drawbacks. As we said in the first place, the only true alternative is to build a larger MSRC, not always a viable option.

## CONCLUSIONS

We have introduced a novel stirring technique, based on the simultaneous excitation of a number of antennas with harmonic signals randomly modulated. The technique, named MAS, has been shown to strongly improve the performance of a MSRC in its lower frequency range, and solve the problem of the inability of multiple-antenna excitation techniques in effectively stirring the field within the MSRC.

Future work is required in order to assess the energy efficiency of this method, and the eventuality of associating it to standard stirring techniques as a mean for improving the field uniformity.

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